SPECIFICATION

TO ALL WHOM IT MAY CONCERN:

      BE IT KNOWN THAT WE, Shinichiro Tago, a citizen of
Japan residing at Kawasaki, Japan, Tomohiro Yamana, a
citizen of Japan residing at Kawasaki, Japan and Yoshimasa
Takebe, a citizen of Japan residing at Kawasaki, Japan have
invented certain new and useful improvements in

      APPARATUS FOR BRANCH PREDICTION BASED ON
              HISTORY TABLE

of which the following is a specification : -

TITLE OF THE INVENTION

APPARATUS FOR BRANCH PREDICTION BASED ON HISTORY TABLE

5 **BACKGROUND OF THE INVENTION**

1. Field of the Invention

The present invention generally relates to methods of predicting branching of branch instructions and processors employing such methods,
10 and particularly relates to a method of predicting branching of branch instructions based on PHT (pattern history table) and a processor employing such a method.

2. Description of the Related Art
15 In processors based on pipeline operations, waiting for branch results to be known before jumping to branch addresses results in the delay of instruction fetch timing, causing disturbance in the pipeline operation. It is thus necessary to predict
20 branching before actually executing branch instructions, thereby making it possible to fetch instructions in a continuous stream in accordance with the pipeline operations.

Branch instructions often have locally
25 lopsided tendency in branch directions such that a given branch direction, of itself, is likely to branch or is not likely to branch. Further, branch directions may often have globally lopsided tendency in branch directions such that a given branch
30 instruction is likely to branch or is not likely to branch depending on the branching results of recently executed branch instructions. A PHT (pattern history table) provides a highly accurate prediction by taking into account the local tendency
35 and the global tendency in branch directions.

Fig.1 is a block diagram showing a configuration of a related-art branch prediction

mechanism based on the PHT.

The branch prediction mechanism of Fig.1 includes an XOR circuit 11, a GHR unit 12, and a PHT unit 13. The GHR (global history register) unit 12 is a register that stores therein the history of recently executed branch instructions as to whether or not they branched. When a given branch instruction branches, the contents of the register is shifted one bit to the left, with "1" being inserted into the least significant bit. When a given branch instruction does not branch, the contents of the register is shifted one bit to the left, with "0" being inserted into the least significant bit. For example, the GHR unit 12 may be 6 bits in length, and the current contents thereof are "011001". If the execution of a given branch operation results in branching, the contents of the GHR unit 12 is shifted one bit to the left, and "1" is inserted into the least significant bit. As a result, the contents of the GHR unit 12 in this case becomes "110011". "110011" indicates branching taking place 6 branch instructions ago, branching taking place 5 branch instructions ago, no branching taking place 4 branch instructions ago, no branching taking place 3 branch instructions ago, branching taking place 2 branch instructions ago, and branching taking place for the last branch instruction.

The XOR circuit 11 performs an Exclusive-OR operation between the contents of the GHR unit 12 and a branch instruction address that is indicated by a program counter 10 as a next instruction to be executed. The obtained Exclusive-OR value is supplied to the PHT unit 13 as an index.

The PHT unit 13 is a RAM (random access memory) that stores therein a count value for each index where the count value may be comprised of 2

bits, for example. Each index is an Exclusive-OR value between the contents of the GHR unit 12 and a branch instruction address indicated by the program counter 10. The 2-bit count value that is an entry corresponding to each index is a prediction used when the corresponding index is hit. When the count value is 0 or 1, branching is predicted. When the count value is 2 or 3, no branching is predicted.

If the contents of the GHR unit 12 are "110011", and the branch instruction address is "001000", for example, the index will be "111011". The 2-bit count value corresponding to this index "111011" is referred to, and may be found to be 2, for example. Since the count value being 2 or 3 indicates branching as described above, the branch instruction at the instruction address "001000" to be executed is expected to branch according to the prediction. If the instruction actually branches as a result of actual execution thereof, the count value is incremented by 1. If the instruction does not branch as a result of actual execution thereof, the count value is decreased by 1. Accordingly, the count value will be 3 in the case of actual branching of the instruction.

After this, the branch instruction at the same branch instruction address "001000" may be executed again while the GHR unit 12 has the same contents "110011" as before. In this case, the index will be "111011", which is the same as before. Since the count value is 3, it is predicted that the branch instruction will branch. As previously described, the contents of the GHR unit 12 are the history of outcomes of recently executed branch instructions. As a result, if the same branch instruction is executed under the same conditions of recent branch outcomes, the branch result is accumulated in the same index. When the same index

is referred to on a next occasion, the count value accumulated in this manner will be used for branch prediction.

The contents of the GHR unit 12 may be "110010", for example, illustrating a case in which the history of outcomes of recently executed branch operations is slightly different from the history of the previous example. This corresponds to a case in which the outcome of the last branch instruction is different from "110011". When the branch instruction at the same branch instruction address "001000" is to be executed, the index will be "111010". In this manner, this index will have branch outcomes accumulated therein when the branch instruction at the branch instruction address "001000" is executed under the previous branch conditions that are indicated as the history "110010".

Accordingly, if only one branch instruction is present in a program, indexes will accumulate the outcomes of this single branch instruction with respect to respective branch histories. This achieves a highly accurate prediction by taking into account each one of the branch histories. If more than one branch instruction is present in a program, however, the outcomes of different branch instructions interfere with each other in the PHT unit 13, thereby degrading prediction accuracy. For example, if the contents of the GHR unit 12 are "111010" and the branch instruction at the branch instruction address "000001" is to be executed, the index will be "111011". This index is identical to the index that is used when the contents of the GHR unit 12 are "110011" and the branch instruction address is "001000". In this manner, the method of calculating an index by the XOR circuit 11 results in the shared use of an index by different branch

instructions, which results in interference between records of branch outcomes and a resulting degradation of prediction accuracy.

In order to avoid the degradation of prediction accuracy, indexes may be generated by combining the contents of the GHR unit 12 and the contents of the program counter 10. If the contents of the GHR unit 12 is "110011" and the branch instruction address is "001000", for example, the index is generated as "110011001000". In such a configuration, however, the number of entries in the RAM of the PHT unit 13 greatly increases. As a matter of fact, the number of entries in this example increases 64 times ($= 2^6$).

In the configuration in which entries in the PHT used for branch prediction interfere with each other as described above, the accuracy of branch prediction undesirably decreases. It is undesirable, however, to excessively increase the memory volume of the PHT for the purpose of improving the prediction accuracy. A desirable configuration is that which enhances the prediction accuracy as much as possible with as small a memory volume as possible.

Accordingly, there is a need for a method of and an apparatus for predicting branching based on the PHT that improves prediction accuracy as much as possible with as small a memory volume as possible by avoiding entry interference.

SUMMARY OF THE INVENTION

It is a general object of the present invention to provide a branch prediction method and a branch prediction apparatus that substantially obviate one or more of the problems caused by the limitations and disadvantages of the related art.

Features and advantages of the present

invention will be set forth in the description which
follows, and in part will become apparent from the
description and the accompanying drawings, or may be
learned by practice of the invention according to
5   the teachings provided in the description. Objects
as well as other features and advantages of the
present invention will be realized and attained by a
branch prediction method and a branch prediction
apparatus particularly pointed out in the
10   specification in such full, clear, concise, and
exact terms as to enable a person having ordinary
skill in the art to practice the invention.

To achieve these and other advantages and
in accordance with the purpose of the invention, as
15   embodied and broadly described herein, an apparatus
for branch prediction according to the present
invention includes a history register which stores
therein history of previous branch instructions, an
index generation circuit which generates a first
20   index from an instruction address and the history
stored in the history register, a history table
which stores therein a portion of the instruction
address as a tag and a first value indicative of
likelihood of branching in association with the
25   first index, a branch destination buffer which
stores therein a branch destination address or
predicted branch destination address of an
instruction indicated by the instruction address and
a second value indicative of likelihood of branching
30   in association with a second index that is at least
a portion of the instruction address, and a
selection unit which makes a branch prediction by
selecting one of the first value and the second
value.
35   In the apparatus as described above, the
selection unit selects the first value if the branch
destination buffer has an entry therein

corresponding to a current instruction address and
the history table has an entry therein corresponding
to the current instruction address and current
history, and selects the second value if the branch
5   destination buffer has an entry therein
corresponding to the current instruction address and
the history table does not have an entry therein
corresponding to the current instruction address and
the current history.

10   In the apparatus as described above, the
provision of a portion of an instruction as a tag in
the history table (PHT) makes it possible to avoid
interference of PHT entries between different branch
instructions. When a tag does not match a current
15   instruction upon reference to the first index, this
means that information about the current instruction
under the current history condition is not
registered. In this case, the branch destination
buffer (BTB) is used for branch prediction. Namely,
20   the first value of the history table is used for
branch prediction if the history table hits (i.e.,
if a tag matches), whereas the second value of the
branch destination buffer is used for branch
prediction if the history table misses (i.e., if a
25   tag does not match).

          In the branch prediction according to the
present invention, highly accurate branch
predictions can be made by avoiding entry
interference, so that even when an instruction is
30   fetched based on the prediction before a branch
direction is actually determined, there is only a
small possibility of miss prediction, thereby making
it possible to avoid disturbance in the pipeline
operation.

35   Other objects and further features of the
present invention will be apparent from the
following detailed description when read in

conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig.1 is a block diagram showing a configuration of a related-art branch prediction mechanism based on the PHT;

Fig.2 is a block diagram of a branch prediction apparatus based on the use of a PHT according to the present invention;

Fig.3 is a flowchart of branch prediction according to the present invention;

Fig.4 is a flowchart of a data updating process according to the present invention;

Fig.5 is a chart showing an example of a program that includes branch instructions; and

Fig.6 is a block diagram of a processor that employs the branch prediction apparatus of the present invention.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

In the following, embodiments of the present invention will be described with reference to the accompanying drawings.

Fig.2 is a block diagram of a branch prediction apparatus based on the use of a PHT according to the present invention.

The branch prediction apparatus according to the present invention includes an XOR circuit 21, a GHR unit 22, a tag-attached PHT unit 23, a comparison unit 24, a BTB (branch target buffer) 25, a comparison unit 26, and a selection unit 27.

The GHR (global history register) unit 22 is a register that stores therein the history of recently executed branch instructions as to whether or not they branched. When a given branch instruction branches, the contents of the register is shifted one bit to the left, with "1" being

inserted into the least significant bit. When a given branch instruction does not branch, the contents of the register is shifted one bit to the left, with "0" being inserted into the least

5 significant bit. The XOR circuit 21 performs an Exclusive-OR operation between the contents of the GHR unit 22 and a branch instruction address that is indicated by a program counter 20 as a next instruction to be executed. The obtained Exclusive-

10 OR value is supplied to the tag-attached PHT unit 23 as an index.

The tag-attached PHT unit 23 is a RAM that stores therein a tag 23a and a count value 23b with respect to each index that is an output of the XOR

15 circuit 21. The BTB unit 25 is a RAM that stores therein a tag (a portion of an instruction address) 25a, a branch destination address 25b of a branch instruction, and a bias bit 25c in association with an index that is a portion of the instruction

20 address).

The BTB unit 25 is used in the related-art branch prediction mechanism, and is provided for the purpose of providing a branch destination address promptly upon the prediction that the branch

25 instruction will branch. A branch destination address can generally be computed when decoding and executing the fetched branch address, so that it takes time to identify the branch destination address. The BTB stores therein branch destination

30 addresses with respect to respective branch instructions, thereby making it possible to read a branch destination address immediately from the BTB upon the prediction that the branch instruction will branch. In order to keep the memory volume of the

35 BTB small, a portion of an instruction address is used as an index, and a remaining portion is used as a tag, which is stored as one of the entries of the

corresponding index.

When an instruction address is supplied
from the program counter 20, a tag 25a is read from
an index corresponding to this instruction address.
5 The retrieved tag 25a is compared with a
corresponding portion of the supplied instruction
address. If the comparison indicates a match
("hit"), it is learned that a branch instruction of
this instruction address is registered, so that the
10 branch destination address 25b associated with this
index is used as a pre-fetch address.

The bias bit 25c indicates the likelihood
of a given branch instruction branching (or not
branching). When this bias bit 25c is comprised of
15 1 bit, "1" indicates that it is likely to branch,
and "0" indicates that it is not likely to branch,
for example. The bias bit 25c corresponds to
information about local tendency in branch
directions that indicates the likelihood of
20 branching with respect to the branch instruction
itself.

The tag-attached PHT unit 23 uses as an
index the Exclusive-OR value between the portion of
the instruction address and the contents of the GHR
25 unit 22 obtained by the XOR circuit 21, and stores
therein information about past branch outcomes as
the count value 23b. In the present invention, the
tag-attached PHT unit 23 stores therein not only the
count value 23b but also a portion of the
30 instruction address as a tag 23a.

When the XOR circuit 21 obtains an index
from the instruction address of the program counter
20 and the contents of the GHR unit 22, the tag 23a
is read from the tag-attached PHT unit 23, and is
35 compared with a corresponding portion of the
instruction address. This comparison is performed
by the comparison unit 24. If the comparison

indicates a match ("hit"), it is ascertained that
the tag-attached PHT unit 23 has a registered entry
of the information about the branch instruction of
this instruction address under the condition of
history indicated by the contents of the GHR unit 22.
In this case, the count value 23b stored in
association with the index is used for branch
prediction.   The count value 23b is stored in a 2-
bit counter, for example.   The count value being 0
or 1 predicts no branching, and the count value
being 2 or 3 predicts branching.

The provision of the tag 23a makes it
possible to avoid interference of PHT entries
between different branch instructions.   When a given
index is referred to, and the tag 23a does not match
the current instruction ("miss"), information about
this instruction under the condition of relevant
history is not registered.   In this case, the
present invention uses the bias bit 25c of the BTB
unit 25 for branch prediction.

Namely, if the tag-attached PHT unit 23
provides a hit (i.e., if the tag matches), the count
value 23b of the tag-attached PHT unit 23 is used
for branch prediction.   If access to the tag-
attached PHT unit 23 results in a miss (i.e., if the
tag does not match), the bias bit 25c of the BTB
unit 25 is used for branch prediction.   This
selection is performed by the selection unit 27.
The selection unit 27 detects whether the tag-
attached PHT unit 23 hits based on the comparison
made by the comparison unit 24.   Based on this
detection, the comparison unit 24 selects the count
value 23b of the tag-attached PHT unit 23 or the
bias bit 25c of the BTB unit 25, and makes branch
prediction based on the selected data, followed by
outputting a branch prediction result.   If the BTB
unit 25 does not hit, a prediction result that

indicates no branching without exception will be output since the branch destination address 25b is not available.

Fig.3 is a flowchart of branch prediction according to the present invention.

At step S1, a check is made as to whether the BTB unit 25 hits. If it hits, the procedure goes to step S3. In the case of a miss, the procedure goes to step S2.

At step S2, since the BTB unit 25 does not hit and the branch destination address 25b is not available, a prediction that there will no branching is made.

At step S3, a check is made as to whether the tag-attached PHT unit 23 hits. If it hits, the procedure goes to step S5. In the case of a miss, the procedure goes to step S4.

At step S4, a branch prediction is made based on the bias bit 25c of the BTB unit 25.

At step S5, a branch prediction is made based on the count value 23b of the tag-attached PHT unit 23.

Fig.4 is a flowchart of a data updating process according to the present invention.

At step S1, a check is made as to whether the BTB unit 25 hits. If it hits, the procedure goes to step S3. In the case of a miss, the procedure goes to step S2.

At step S2, the instruction address that did not hit is registered in the BTB unit 25 together with the branch destination address. In this case, the outcome of the actually executed instruction as to whether it branched is stored as the bias bit 25c in the BTB unit 25. That is, as a result of actual execution of the instruction, "1" is stored as the bias bit 25c in the case of branching, and "0" is stored as the bias bit 25c in

the case of no branching.

At step S3, since access to the BTB unit
25 hits, the relevant instruction address in the BTB
unit 25 is updated.

At step S4, a check is made as to whether
access to the tag-attached PHT unit 23 hits. If it
hits, the procedure goes to step S8. In the case of
a miss, the procedure proceeds to step S5.

At step S5, a check is made as to whether
an actual branch direction upon the actual execution
of the instruction matches the branch prediction.
In this case, the branch prediction was made based
on the bias bit 25c of the BTB unit 25 since access
to the tag-attached PHT unit 23 has missed. If the
check indicates a match, the procedure goes to step
S6. Otherwise, the procedure goes to step S7.

At step S6, the procedure comes to an end
without taking any further action. This is because
it is fair to assume that the present branch
prediction is proper if the result of branch
prediction matches the outcome of an actual branch
operation.

At Step S7, information about the
instruction under the current history condition is
registered in the tag-attached PHT unit 23. Namely,
under the relevant index, the tag 23a of the
instruction address is stored, and the actual branch
outcome is stored as the count value 23b. In the
case of branching, 2 ("10") is stored, and, in the
case of no branching, 1 ("01") is stored, for
example. This operation is performed because it is
fair to determine that the current branch prediction
based on the bias bit 25c of the BTB unit 25 is not
proper if the result of branch prediction does not
match the outcome of an actual branch operation.

At step S8, since access to the tag-
attached PHT unit 23 hits, the count value 23b of

the tag-attached PHT unit 23 is updated. In detail,
the count value 23b is incremented by 1 in the case
of actual execution having resulted in branching,
and is decreased by 1 in the case of the actual

5   execution having resulted in no branching. If the
count value 23b is already its maximum value (e.g.,
3 in the case of a 2-bit counter), the count value
23b stays unchanged even if the outcome of actual
execution results in branching. If the count value

10 23b is already its minimum value (e.g., 0), the
count value 23b stays unchanged even if actual
execution results in no branching.

At step S9, each of the bias bit 25c of
the BTB unit 25 and the count value 23b of the tag-

15 attached PHT unit 23 is checked. If the bias bit
25c and the count value 23b are respectively 0 and 0
("00") or are 1 and 3 ("11"), the procedure goes to
step S11. Otherwise, the procedure proceeds to step
S10.

20   At step S10, an LRU bit or the like is
updated. Here, the LRU bit is attached to each
entry of the tag-attached PHT unit 23, and indicates
the entry that has not been used for the longest
period of time since the last access. Each time the

25 tag-attached PHT unit 23 is used for branch
prediction, this LRU bit is updated. The
significance of the LRU bit will be described later.

At step S11, the relevant entry of the
tag-attached PHT unit 23 is invalidated. That is,

30 the relevant entry of the tag-attached PHT unit 23
is deleted, or is deleted in effect. If the count
value 23b of the tag-attached PHT unit 23 strongly
indicates a particular branch direction, and if the
bias bit 25c of the BTB unit 25 also indicates the

35 same branch direction, the same branch prediction
will be obtained even when the bias bit 25c of the
BTB unit 25 is used for branch prediction. In this

case, the deletion of a relevant entry from the tag-attached PHT unit 23 achieves efficient use of memory space in the RAM of the tag-attached PHT unit 23.

5   In this manner, the data updating process of the present invention is performed.

In the following, a set associative method according to the present invention will be described.

In the present invention, more than one

10 tag-attached PHT unit 23 may be provided as shown in Fig.2. The provision of a plurality of the tag-attached PHT units 23 makes it possible to store a plurality of entries for a single index. In a four-way set associative configuration having 4 sets of

15 PHTs, as many as four entries can be stored with respect to a single index.

When a set associative configuration is employed, it is necessary to determine which entry should be deleted at the time of data updating. If

20 a fifth entry needs to be stored when four entries are already in use in the four-way set associative configuration, it is necessary to select and delete one of the four entries. At step S7 of Fig.4, for example, information about the instruction under the

25 current history condition is registered in the tag-attached PHT unit 23, one of the existing entries needs to be deleted and replaced by a new entry if the relevant index is already filled with entries.

The LRU bit, which was described in

30 connection with step S10 of Fig.4, is used to identify the entry to be replaced when an existing entry needs to be replaced by a new entry. The LRU bit is provided for each entry, and indicates the order at which entries were referred to. By

35 checking this LRU bit, an entry that has not been used for the longest period of time since the last access thereto can be identified and replaced by a

new entry.

The use of a LRU bit is only an example of various methods that can be used to identify an entry to be replaced. Other methods include, but are not limited to, an LFU (least frequently used) method that replaces an entry of the least frequent use, an FIFO (first-in first-out) method that replaces an entry that is the oldest to be registered, and a random method that replaces a randomly selected entry.

In the case in which only one tag-attached PHT unit 23 is provided without use of a set associative method, each index allows only one entry to be stored. When new information needs to be registered in the tag-attached PHT unit 23 in such a case, an existing entry is deleted and replaced by a new entry if the existing entry is another instruction address registered under the currently referenced index.

As shown in Fig.2, a set associative method may also be used with respect to the BTB unit 25.

In the following, branch prediction according to the present invention will be described with reference to a specific program example.

Fig.5 is a chart showing an example of a program that includes branch instructions.

The length of the GHR unit 22 is 6 bits, which are initially set to "000000".

When access is made to the BTB unit 25 under the index "0001" at the time of executing an instruction at the instruction address "000001", a tag miss is detected, and, thus, no branching is predicted. This corresponds to step S2 of Fig.3. As a result of actual execution of the instruction, the branch instruction branches, being contrary to the prediction. A tag "00", a bias "1", and a

branch destination address "000011" are registered
in the BTB unit 25 under the index "0001". This
corresponds to step S2 of Fig.4.

The GHR unit 22 is shifted one bit to the
left, and "1" indicative of branching is inserted
into the least significant bit, resulting in
"000001". At this point of time, the prediction
result and the contents of each register/memory are:
    PC=000001, prediction failure,
    BTB[0001]=00-1-000011, and GHR:000001.
Here, PC indicates a program counter, and the
contents of the BTB are shown as a tag "00", a bias
"1", and a branch destination address "000011" in
this order.
    At the instruction address "000100", access to
the BTB unit 25 is made under the index "0100", and
a tag miss is detected, resulting in the prediction
indicating no branching. As a result of actual
execution of the instruction, the branch instruction
does not branch, thereby agreeing with the
prediction. A tag "00" and a bias "0" are
registered in the BTB unit 25 under the index "0100".

The GHR unit 22 is shifted one bit to the
left, and "0" indicative of no branching is inserted
into the least significant bit, resulting in
"000010". At this point of time, the prediction
result and the contents of each register/memory are:
    PC=000001, prediction success,
    BTB[0100]=00-0-******, and GHR:000010.

After this, instructions at the
instruction addresses "0005", "0006", "0007", and
"0008" do not branch. In the same manner as above,
the results are:
    PC=000101, prediction success,
    BTB[0101]=00-0-******, GHR=000100;

    PC=000110; prediction success,

BTB[0110]=00-0-******, GHR:001000;

PC=000111, prediction success,
BTB[0111]=00-0-******, GHR=010000; and

PC=001000, prediction success,
BTB[1000]=00-0-******, GHR=100000.

At the instruction address "001100", access to the BTB unit 25 is made under the index "1100", and a tag miss is detected, resulting in the prediction indicating no branching. As a result of actual execution of the instruction, the branch instruction branches, being contrary to the prediction. A tag "00", a bias "1", and a branch destination address "001001" are registered in the BTB unit 25 under the index "1100".

The GHR unit 22 is shifted one bit to the left, and "1" indicative of branching is inserted into the least significant bit, resulting in "000001". At this point of time, the prediction result and the contents of each register/memory are:

PC=001100, prediction failure,
BTB[1100]=00-1-001001, and GHR=000001.

Since the execution of the program has branched to the instruction address "001001", access to the BTB unit 25 under the index "1100" is made again at the instruction address "001100". At this time, a tag hit is detected, and a branch destination address "001001" is obtained. Since the access to the BTB unit 25 provides a tag hit, a check is made as to whether access to the tag-attached PHT unit 23 results in a tag hit. This corresponds to step S3 of Fig.3.

In detail, access to the tag-attached PHT unit 23 is made by using as an index an Exclusive-OR value "001101" between the address "001100" and the GHR contents "000001". Since a tag check results in

a miss, branching to an address "001001" is predicted based on the bias bit of the BTB unit 25. This corresponds to step S4 of Fig.3. As a result of actual execution of the instruction, the branch instruction branches to "001001", agreeing with the prediction. As in step S6 of Fig.4, therefore, the BTB unit 25 and the tag-attached PHT unit 23 are not updated. At this point of time, the prediction result and the contents of each register/memory are:

     PC=001100, prediction success,

     BTB[1100]=00-1-001001 (with no updating),

     and GHR=000011.

     When a loop is repeated three times by the branch instruction at the instruction address "001100", the results are:

     PC=001100, prediction success,

     BTB[1100]=00-1-001001 (with no updating),

     GHR=000111;

     PC=001100, prediction success,

     BTB[1100]=00-1-001001 (with no updating),

     GHR=001111; and

     PC=001100, prediction success,

     BTB[1100]=00-1-001001 (with no updating),

     GHR=011111.

     After repeating the loop six times (branching five times), branching to an address "001001" is predicted in the same manner as before at the instruction address "001100". In this case, since the loop comes to an end at the sixth time, the branch instruction does not branch, not agreeing with the prediction. Consequently, as shown at step S7 of Fig.4, a tag "1100" and a count value "0" are registered under the index that is an Exclusive-OR value "010011" between the instruction address "001100" and the GHR contents "011111". At this

point of time, the prediction result and the
contents of each register/memory are:
        PC=001100, prediction failure,
        PHT[010011]=1100-0, and GHR=111110.
5   Thereafter, when program execution at the
instruction address "001111" branches to an
instruction address "000010", the results are:
        PC=001111, prediction failure,
        BTB[1111]=00-1-000010, and GHR=111101.
10   After this, instructions at the
instruction address "000010" and the following
instruction addresses are executed again. This time,
the results are:
        PC=000100, prediction success (no branching),
15   BTB and PHT: no update, GHR=111010;

        PC=000101, prediction success (no branching),
        BTB and PHT: no update, GHR=110100;

20   PC=000110, prediction success (no branching),
        BTB and PHT: no update, GHR=101000;

        PC=000111, prediction success (no branching),
        BTB and PHT: no update, GHR=010000;
25
        PC=001000, prediction success (no branching),
        BTB and PHT: no update, GHR=100000;

        PC=001100, prediction success (branch),
30   BTB and PHT: no update, GHR=000001;

        PC=001100, prediction success (branch),
        BTB and PHT: no update, GHR=000011;

35   PC=001100, prediction success (branch),
        BTB and PHT: no update, GHR=000111;

PC=001100, prediction success (branch),
BTB and PHT: no update, GHR=001111;

PC=001100, prediction success (branch),
BTB and PHT: no update, GHR=011111; and

PC=001100, prediction success (no branching),
PHT[010011]=1100-0, GHR=111110.

Here, when the branch instruction at the instruction
address "001100" is executed at the last run of the
loop, no branching is predicted. This is because
both the BTB unit 25 and the tag-attached PHT unit
23 hit, and the count value 23b of the tag-attached
PHT unit 23 is zero. At the last branch instruction,
the results are:

PC=001111, prediction success (branch),
BTB and PHT: no update, and GHR=111101.

In this manner, all the predictions are
successful this time.

In executing this program, the branch
prediction method according to the present invention
uses only one entry in the tag-attached PHT unit 23.
In this manner, the branch prediction method of the
present invention can achieve a highly accurate
prediction even when the memory space of the RAM is
rather small.

It should be noted that the related-art
branch prediction method shown in Fig.1 cannot be
successful in all the predictions when executing the
instructions at the instruction address "000010" and
the following instruction addresses a second time in
the above program. This is because there is
interference between PHT entries.

Fig.6 is a block diagram of a processor
that employs the branch prediction apparatus of the
present invention.

A processor 100 of Fig.6 includes an

instruction cache 101, a data cache 102, an
instruction fetch unit 103, an instruction execution
control unit 104, a register 105, a register 106,
and execution units 107 through 110.

5   The instruction cache 101 and the data
cache 102 temporarily store therein instructions and
data, respectively. The instruction fetch unit 103
successively fetches instructions from the
instruction cache 101 as they are pointed to by the
10 program counter. The instruction execution control
unit 104 successively decodes the instructions
fetched by the instruction fetch unit 103, and
controls the instruction execution according to the
decoded results. The register 105, register 106,
15 and execution units 107 through 110 together make up
an execution operation unit. The execution
operation unit operates under the control of the
instruction execution control unit 104, and carries
out executions according to instruction. The
20 execution units 107 through 110 execute instructions
0 through 3, respectively, independently of each
other, thereby making a configuration that can carry
out pipeline operations at high speed.

        The branch prediction apparatus according
25 to the present invention shown in Fig.2 is provided
in the instruction fetch unit 103. When there is a
branch instruction, the branch prediction apparatus
predicts a branch direction, so that an instruction
corresponding to the predicted branch direction will
30 be fetched. In the branch prediction according to
the present invention, highly accurate branch
predictions can be made by avoiding entry
interference, so that even when an instruction is
fetched based on the prediction before a branch
35 direction is actually determined, there is only a
small possibility of miss prediction, thereby making
it possible to avoid disturbance in the pipeline

operation.

Further, the branch prediction according to the present invention uses the bias bit 25c of the BTB unit 25, so that the time length necessary

5 to make branch outcomes properly learned can be relatively short compared with a related-art case in which a PHT alone is used for branch prediction. The branch prediction according to the present invention is thus capable of coping with situational

10 changes caused by context switches in a short time. In the benchmark jpeg, jbig, mpeg4, ghostscript using a 8-KB RAM, the branch prediction of the present invention attained 96% prediction accuracy.

Further, the present invention is not

15 limited to these embodiments, but various variations and modifications may be made without departing from the scope of the present invention.

The present application is based on Japanese priority application No. 2001-186473 filed

20 on June 20, 2001, with the Japanese Patent Office, the entire contents of which are hereby incorporated by reference.